High p_{t} Measurements at the CERN SPS

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Abstract

The current experimental situation concerning high p_{t} observables at the CERN SPS is reviewed. Recent data from the NA45, NA49 and NA57 collaborations are discussed and compared to earlier measurements by WA98 and NA45 at the same center-of-mass energies, as well as to measurements at the higher energies by the RHIC experiments. The observables include new p+p, A+A spectra, nuclear modification factors (R_{AA}, R_{CP}), two particle azimuthal correlations, and baryon to meson ratios at moderately high p_{t}. Generally, the interpretation of the SPS data suffers from the lack of reliable baseline measurements (p+p and p+A). However, the overall picture that is emerging suggests that already at SPS energies medium effects similar to those observed at RHIC are present.

1 Introduction

At RHIC energies a strong suppression of high p_{t} hadron production in nucleus–nucleus collisions relative to p+p collisions has been observed [1,2], which is usually attributed to the energy loss that the parent partons experience when transversing the color deconfined medium present in these collisions [3]. Also, two particle correlations at high p_{t} indicate a strong effect of the produced medium on the hadron emission pattern. At the lower SPS energies on the other hand, the experimental situation was rather unclear and even contradictory. While, e.g. the energy density derived from the measured E_{t} distributions, as well as the fact that the chemical freeze-out occurs very close to the theoretically expected phase boundary, suggest that a quark gluon plasma is already formed at top SPS energies [4], there was so far no indication of any high p_{t} suppression at these energies. In fact, the WA98 data on the nuclear modification factor R_{AA} of neutral pions rather exhibited a Cronin–type of enhancement [5]. However, a reassessment of the p+p baseline [6] allowed the conclusion that the data on pion production in central A+A reactions are consistent with the expectation in a jet quenching scenario with gluon densities of $dN_{\mathrm{g}}/dy = 400 - 600$ [7], more in line with the measured hadron multiplicities.

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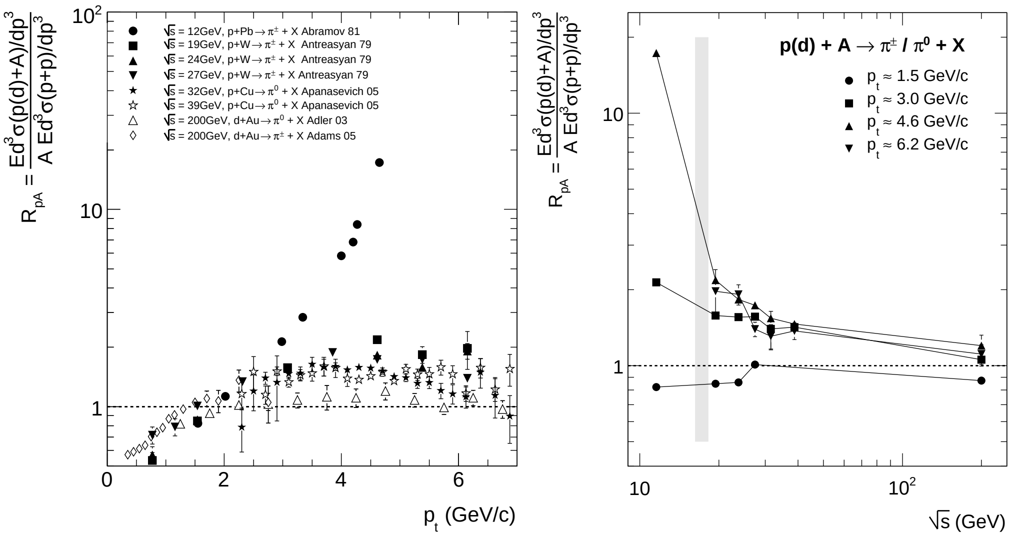

Fig. 1. Left: The nuclear modification factor R_{pA} as a function of p_{t} for charged and neutral pions (minimum bias p(d)+A data [15,16,17,18,19]). Right: R_{pA} at different fixed momenta as a function of $\sqrt{s_{\mathrm{NN}}}$. The grey band indicates the SPS center-of-mass energy.

A first study of two particle azimuthal correlations for $p_{\mathrm{t}} > 1.2$ GeV/c by the NA45 experiment [8], showed a structure that could be interpreted as a correlation of semi-hard particles on top of a collective flow component. Similar to what has been seen at RHIC, the away-side peaks broadens with centrality, which might be attributed to in-medium effects. Recently, new data on R_{CP} for identified particles have been presented by the NA49 and NA57 experiment [9,10]. Additionally, the NA45 collaboration has done a refined analysis of two particle azimuthal correlations at high p_{t} [11]. These data help to clarify the current situation and shall be discussed in the following.

2 Baseline measurements in p+p and p+A

In order to establish whether any kind of modification in the high p_{t} region is present in A+A collisions, reference data from p+p and p+A collisions are of high importance. Unfortunately, there are no p+p(A) data available at $\sqrt{s} = 17.3$ GeV that cover the interesting p_{t}-region for A+A studies above 2 GeV/c. Recently, the NA49 experiment has published charged pion spectra measured at this center-of-mass energy [12], but the statistics limits the p_{t}-reach to 2.1 GeV/c. Several attempts have been made to replace the missing data by an interpolation from lower and higher beam energies [5,6]. In [6] the parametrization suggested by Blattnig et al. [13] was used to construct a p+p baseline for neutral pions. This parametrization also agrees to the charge averaged pion spectra in the region measured by NA49 at $\sqrt{s} = 17.3$ GeV.

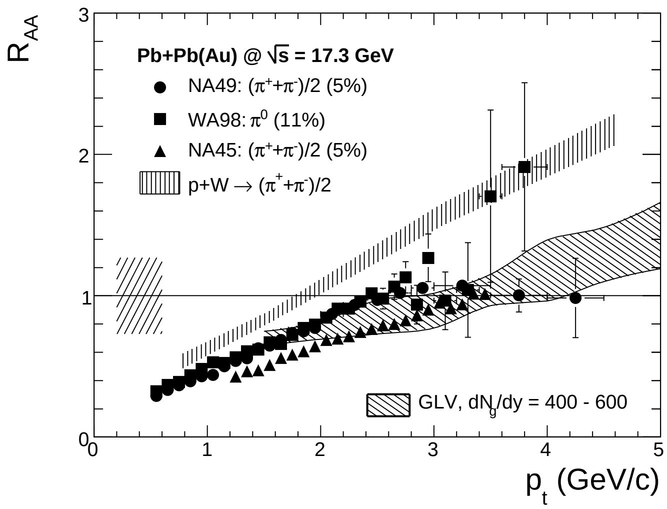

Fig. 2. The nuclear modification factor R_{AA} as a function of p_{t} for neutral and averaged charged pions [5,20,9]. The hatched box represents the typical normalization error from the $\langle N_{\mathrm{coll}} \rangle$ determination. The lower hatched band is a theory prediction including energy loss, Cronin effect and nuclear shadowing [7]. The upper dashed band shows R_{pA} as measured in p+W at $\sqrt{s_{\mathrm{NN}}} = 19.4$ GeV/c [16].

However, one should keep in mind that at the center-of-mass energies under discussion here, the spectral shape in the higher p_{t} region (i.e. above $p_{\mathrm{t}} = 2$ GeV/c) changes drastically with energy since the kinematic limit becomes important here (see e.g. [14]). Therefore, any parametrization introduces a large systematic error. A specific problem in the interpretation of the SPS data arises from the fact that the typical p_{t}-reach is in the region below 4–5 GeV/c. This region is governed by an interplay of the Cronin effect, which causes an enhancement in p+A collisions relative to p+p, and a potential suppression due to jet quenching. A proper understanding of the p+A data is therefore indispensable. This is illustrated by Fig. 1 that shows the existing data on the nuclear modification factor R_{pA}at different center-of-mass energies [15,16,17,18,19]. R_{pA} increases by approximately a factor 2 when going from $\sqrt{s_{\mathrm{NN}}} = 200$ GeV down to $\sqrt{s_{\mathrm{NN}}} = 19.4$ GeV at $p_{\mathrm{t}} \approx 4.6$ GeV/c. This is not unexpected since due to the steeper spectral shape at lower energies R_{pA} is more sensitive to p_{t} broadening effects. According to the data from Serpukhov at $\sqrt{s_{\mathrm{NN}}} = 11.5$ GeV [15], R_{pA} increases towards lower energies even more rapidly, making interpolations very difficult.

3 Nuclear modification factors in A+A

Figure 2 displays the nuclear modification factor R_{AA} for pions based on central A+A data measured by WA98, NA45, NA49 [5,20,9]. Here, R_{AA} was constructed by using the p+p parametrization of Blattnig et al. [13], as al-

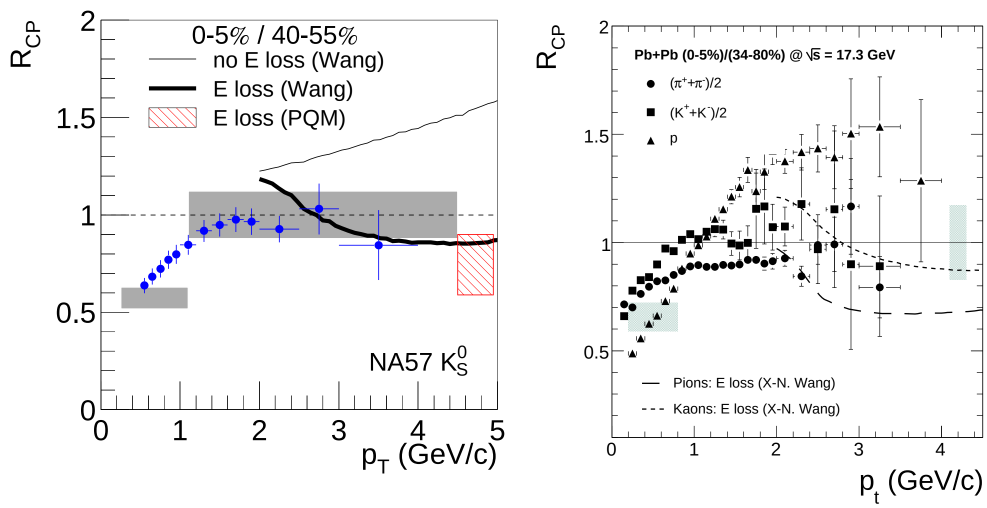

Fig. 3. Left: The nuclear modifcation factor $R_{\rm CP}$ for $\rm K^0_s$ as measured by NA57 [10], compared to predictions with and without parton energy loss [21,22]. Right. $R_{\rm CP}$ for charged pions, charged kaons, and protons measured by NA49 [9]. The dashed (dotted) curves are calculations with parton energy loss for pions (kaons) [21].

ready suggested in [6]. A new feature in this figure are the recent NA49 data that extend the $p_{\rm t}$-reach up to 4.5 GeV$/c$. Bearing in mind all the caveats described in the previous section, the shown $R_{\rm AA}$ values are consistent with the theoretical expectation for an energy loss scenario at realistic gluon densities of $dN_{\rm g}/dy = 400 - 600$ [7]. They are clearly below the $R_{\rm pA}$ values measured at slighly higher $\sqrt{s_{\rm NN}}$, which should provide a lower bound on the expected $R_{\rm pA}$ at SPS.

The problem of the missing p+p baseline measurement can to a certain extent be circumvented by using peripheral A+A collisions as a reference instead. Figure 3 shows the $R_{\rm CP}$ for $\rm K^0_s$ by NA57 (data is also available for $\rm h^-$, Λ, and $\bar{\Lambda}$[10]) and the $R_{\rm CP}$ for pions, kaons, and protons by NA49 [9]. A comparison of the data to calculations including parton energy loss [21,22] shows that the measured $R_{\rm CP}$ values are in line with a quenching scenario. When considering all systematic errors introduced by different methods of centrality determination and the estimation of $\langle N_{\rm coll} \rangle$, the results of NA49, NA57, and WA98 are found to be consistent with each other. The energy dependence of $R_{\rm CP}$ at intermediate $p_{\rm t}$, which is summarized in the left panel of Fig. 4, apparantly is strongest between $\sqrt{s_{\rm NN}} = 17.3$ GeV and $\sqrt{s_{\rm NN}} = 62$ GeV. An interesting question is whether this is just a reflection of a similar energy dependence of the Cronin effect or due to a dramatic increase of the parton energy loss. Data on p(d)+A at $\sqrt{s_{\rm NN}} = 62$ GeV would be needed to provide an answer. As already visible in Fig. 3, there is a clear mass dependence of $R_{\rm CP}$: $R_{\rm CP}(\rm p,\Lambda) > R_{\rm CP}(K) \geq R_{\rm CP}(\pi)$. This effect is quite similar at SPS and RHIC (see right panel of Fig. 4), even though the overall scale is naturally lower at higher energies. However, the same mass dependence is present in

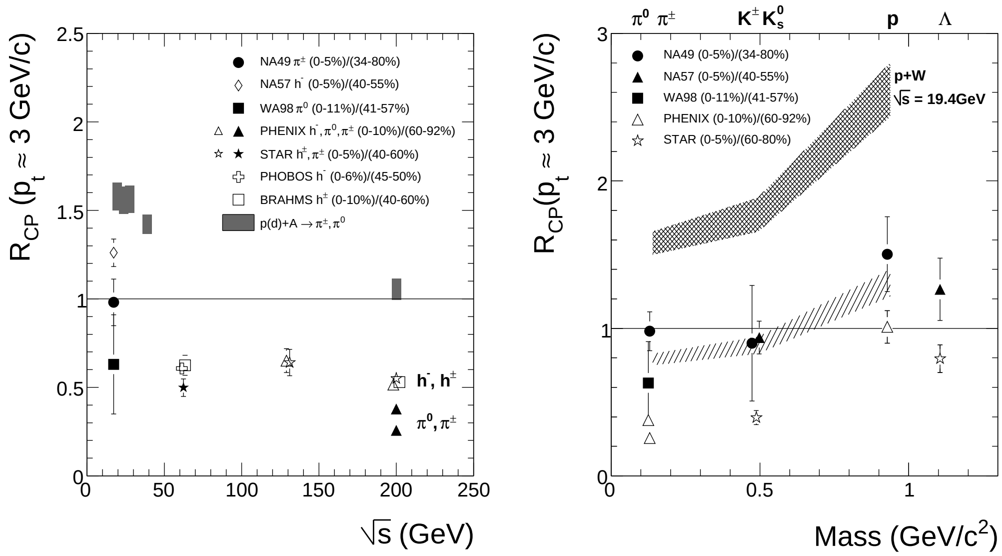

Fig. 4. Left: The energy dependence of the nuclear modification factor R_{CP} for pions and h$^{\pm}$ at $p_{\mathrm{t}} \approx 3$ GeV/c [5,9,10,23,24,2,25,1,26,27,28,29]. Also included is R_{pA} (grey boxes) for p+W at the same p_{t}[16]. Right: The dependence of R_{CP} on the particle mass for SPS ($\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV, filled symbols) [5,9,10] and RHIC ($\sqrt{s_{\mathrm{NN}}} = 200$ GeV, open symbols) [30,31]. The dark grey band represents R_{pA} from p+W data at $\sqrt{s_{\mathrm{NN}}} = 19.4$ GeV [16], while the hatched band displays the same values scaled by 0.5.

R_{pA} at $\sqrt{s_{\mathrm{NN}}} = 19.4$ GeV. Scaled down by a factor 0.5 it nicely matches the data for A+A at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV, while the corresponding factor is 0.2 at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV.

4 High p_{t} correlations

Figure 5 shows the two particle correlation functions $C(\Delta\phi)$, as well as the conditional yields of the jet associated hadrons measurend by NA45 [11] at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV. The method and the choice of the p_{t}-ranges ($2.5\,\mathrm{GeV}/c < p_{\mathrm{t}}^{trigger} < 4.0\,\mathrm{GeV}/c$ and $1.0\,\mathrm{GeV}/c < p_{\mathrm{t}}^{assoc.} < 2.5\,\mathrm{GeV}/c$) are identical to an analysis performed by the PHENIX collaboration at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV [34]. The away side structure observed at SPS is clearly broader than a p+p like di-jet expectation, as e.g. predicted by PYTHIA, and the width does not depend significantly on centrality. However, an indication for a modification of its shape with centrality is observed: The away-side structure seems to develop a flat top for central events. Even though this modification of the shape is much stronger at RHIC, this observations are qualitatively similar at both energies and might in both case be indicative for partonic interaction with the produced medium.

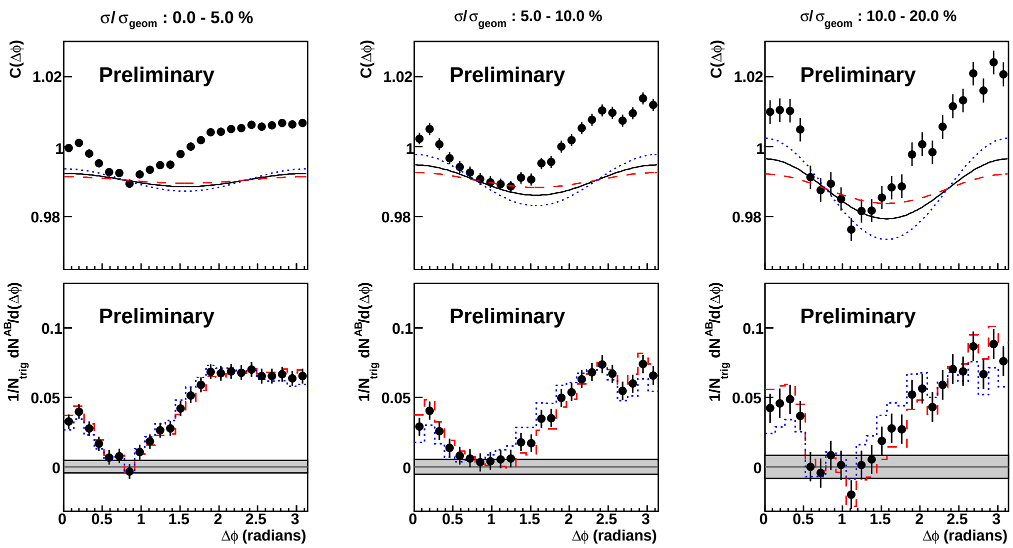

Fig. 5. Upper row: Correlation functions for Pb+Au reactions at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV for three centrality bins. The full line represents the flow contribution estimated via the ZYAM method [34]. The dashed and dotted lines indicated the statistical uncertainty of this contribution. Lower row: Conditional yields of the jet-pair distribution in three centrality bins, normalized to the number of triggers [11].

5 Baryon-meson ratios at high p_{t}

The mass hierarchy observed in the R_{CP} values at SPS might point to the fact that the quark coalescence approach, that has been proposed to explain the large baryon/meson ratios at intermediate p_{t} observed at RHIC [33], might also be valid at SPS energies. The upper panels of Fig. 6 show the p/π^{+}, $\bar{\mathrm{p}}/\pi^{-}$, and $\Lambda/\mathrm{K}^0_{\mathrm{s}}$ ratios as measured by NA49, together with the corresponding results from STAR [33] and PHENIX [34] at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. Generally, the higher net-baryon density at SPS energies manifests itself in the differences in the overall scale of the ratios. What is remarkable though is the fact that shape of the p_{t}-dependence is identical to the one observed at RHIC. The lower panels of Fig. 6 show the double ratios which do not exhibit a significant p_{t}-dependence. A similar observation has been made in the double ratios of R_{CP} by the NA57 collaboration [35]. This would indicate that a possible transition from a hydrodynamical hadronization picture to quark coalescence would happen in the same p_{t}-region at SPS and RHIC.

6 Summary

New data on high p_{t} hadron production at the CERN SPS were reviewed. The interpretation of the nucleus–nucleus high p_{t} data at the SPS generally suffers

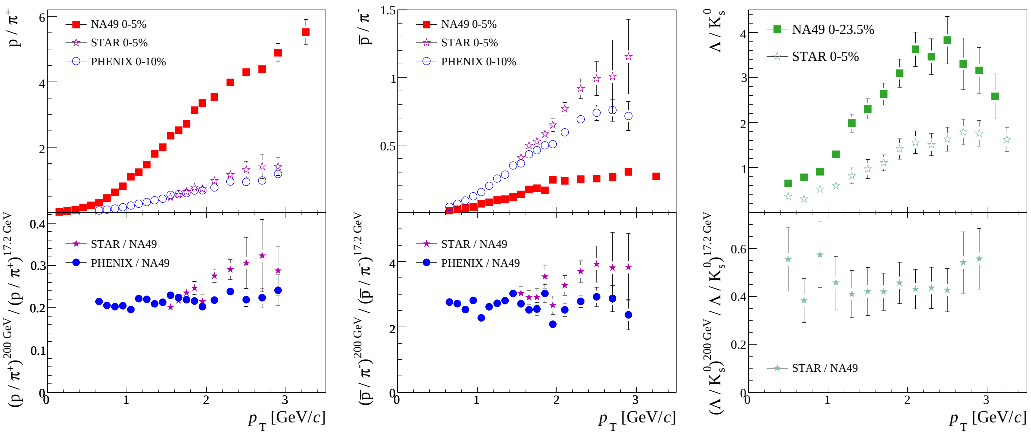

Fig. 6. The baryon/meson ratios as measured by NA49 at $\sqrt{s_{\rm NN}} = 17.3$ GeV [32], compared to results from RHIC at $\sqrt{s_{\rm NN}} = 200$ GeV [33,34]. Please note the different scales of the plots.

from the lack of reliable p+p and p+A baseline measurements in the relevant $p_{\rm t}$-range. This is particularly important here, since the spectral shape changes drastically with energy in the SPS region. Nevertheless, the general picture that emerges from the new data by NA45, NA49, and NA57, as well as from a reassessment of older data (WA98, NA45), is that also at SPS parton energy loss may be present. The $R_{\rm CP}$ values show no sign of Cronin enhancement but rather indicate that the Cronin effect is counterbalanced by jet quenching. Also, two-particle azimuthal correlations exhibit a qualitatively similar behaviour at SPS than at RHIC and might indicate a partonic interaction with the medium. The new SPS data on intermediate $p_{\rm t}$ baryon/meson ratios might help to understand the underlying hadronization mechanisms.

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